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The linear polarization of nearby bright stars measured at the parts per million level

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ABSTRACT

We report observations of the linear polarization of a sample of 49 nearby bright stars measured to sensitivities of between ∼1 and ∼4 $\times 10^{-6}$. The majority of stars in the sample show measurable polarization, but most polarizations are small with 75% of the stars having P < 2 $\times 10^{-5}$. Correlations of the polarization with distance and position, indicate that most of the polarization is of interstellar origin. Polarizations are small near the galactic pole and larger at low galactic latitudes, and the polarization increases with distance. However, the interstellar polarization is very much less than would be expected based on polarization-distance relations for distant stars showing that the solar neighbourhood has little interstellar dust. BS 3982 (Regulus) has a polarization of ∼ 37 $\times 10^{-6}$, which is most likely due to electron scattering in its rotationally flattened atmosphere. BS 7001 (Vega) has polarization at a level of ∼ 17 $\times 10^{-6}$ which could be due to scattering in its dust disk, but is also consistent with interstellar polarization in this direction. The highest polarization observed is that of BS 7405 (α Vul) with a polarization of 0.13%

Key words: polarization – techniques: polarimetric – ISM: magnetic fields.

1 INTRODUCTION

Linear polarization of starlight provides a powerful technique for investigating the nature of the interstellar medium. Interstellar dust particles aligned to the galactic magnetic field produce interstellar polarization, which is one of the main sources of stellar linear polarization. Studies of this polarization provide information on the dust distribution and magnetic field structure (e.g. Heiles 1996) and on the nature and size of the dust particles (Whittet et al. 1992; Kim, Martin & Hendry 1994).

Studies of the polarization of stars close to the Sun have been made by Piirola (1977), Tinbergen (1982) and Leroy (1993a,b, 1999). They found very little polarization in neraby stars. Leroy (1993b) found only 25 stars with definite polarization in a survey of 1000 stars within 50pc. Subsequent analysis showed that almost all of these polarized stars were actually at greater distances when more accurate Hipparcos parallaxes became available (Leroy 1999), and that significant interstellar polarization became detectable at distances of about 70pc in some directions and at 150pc in others. Andersson & Potter (2006) have also reported observations of polarization of southern hemisphere stars, that they attribute to the wall of the Local Bubble at ∼100 pc distance.

All of these studies used polarization measurements with accuracies of, at best, $\sim 10^{-4}$ in fractional polarization. Recently we have built and tested a new polarimeter, PlanetPol, (Hough et al. 2006) capable of measuring stellar linear polarization at the parts per million level. Here we report observations of a sample of nearby bright stars measured to sensitivies of generally better than 3×10^{-6} and in some cases to better than 1×10^{-6} in fractional polarization. This represents an improvement of a factor of 20 to 100 on previous measurements.

In addition to the use of polarization to probe the interstellar medium, it is of interest to know at what level normal stars show intrinsic polarization. There is currently considerable interest in using polarization to study extrasolar planets. Polarization can be used to directly detect unresolved hot-Jupiter type planets (Seager, Whitney & Sasselov 2000; Lucas, Hough & Bailey 2006; Lucas et al. 2009), as a differential technique to detect planets in imaging observations (Schmid et al. 2005; Keller 2006), and as a means of characterizing extrasolar planet atmospheres (Bailey 2007). Significant polarization from the host star could complicate such observations. In the case of the quiet Sun direct observations by Kemp et al. (1987) show linear polarization of $< 3\times10^{-7}$. However, more active stars could show higher polarizations, and polarization might also result from exozodiacal disks around the stars.

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Table 1. Properties of Sample Stars - The horizontal line marks the 17 hour division used in figure 4

BS	Other Names	V mag	Spectral Type	Dist (pc)	RA hh:mm	Dec dd:mm	Galactic Long	Galactic Lat	$v \sin i$ kms^{-1}
3982	Regulus, α Leo	1.35	B7V	23.8	10 08	+11 58	226.4	48.9	353
4031		3.44	F0III	79.6	10 16	+23 25	210.2	55.0	83
4069		3.07	M0III	76.3	10 22	+41 30	177.9	56.4	
4295	Merak, β Uma	2.35	A1V	24.3	11 01	+56 23	149.2	54.8	32
4301	Dubhe, α Uma	1.79	K0Iab	37.9	11 03	+61 45	142.8	51.0	<17
4335		3.01	K1IIII	45.0	11 09	+44 30	165.8	63.2	10
4357		2.56	A4V	17.7	11 14	+20 31	224.2	66.8	180
4359		3.32	A2V	54.5	11 14	+15 26	235.4	64.6	5
4518		3.71	K0.5IIIb	60.1	11 46	+47 47	150.3	28.4	10
4527		4.54	A7V	69.4	11 48	+20 13	235.0	73.9	
4534	β Leo	2.14	A3V	11.1	11 49	+14 34	250.6	70.8	110
4540	β Vir	3.61	F9V	10.9	11 51	+01 46	270.5	60.8	3
4905		1.76	A0p	24.8	12 54	+55 58	122.2	61.2	33
4910		3.38	M3III	62.1	12 56	+03 24	305.5	66.2	
4915	α^2 CVn	2.90	A0p	33.8	12 56	+38 19	118.3	78.8	
4932		2.83	G8III	31.3	13 02	+10 58	312.3	73.6	8
5054	Mizar	2.27	A2V	24.0	13 24	+54 56	113.1	61.6	13
5191		1.85	B3V	30.9	13 47	+49 19	100.7	65.3	226
5235		2.68	G0IV	11.3	13 55	+18 24	5.3	73.0	18
5340	Arcturus, α Boo	−0.04	K1.5III	11.3	14 16	+19 11	15.1	69.1	8
5429		3.58	K3III	45.6	14 32	+30 22	47.3	67.8	8
5435		3.00	A7III	26.1	14 32	+38 18	67.3	66.2	135
5563		2.08	K4III	38.8	14 51	+74 09	112.6	40.5	8
5793	α CrB	2.21	A0V	22.9	15 35	+26 43	41.9	53.8	132
5849		3.84	B9IV	44.5	15 43	+26 18	41.7	51.9	100
5854		2.64	K2IIIb	22.5	15 44	+06 26	14.2	44.1	8
6092		3.74	B5IV	96.4	16 20	+46 18	72.5	45.0	20
6095		3.74	A9III	59.9	16 22	+19 09	35.3	41.3	135
6148		2.79	G7IIIa	45.3	16 30	+21 29	39.0	40.2	10
6149		3.90	A0V	50.9	16 31	+01 59	17.1	31.8	142
6212		2.89	G0IV	10.8	16 41	+31 36	52.7	40.3	5
6299		3.20	K2III	26.3	16 58	+09 23	28.4	29.5	8
6324		3.91	A0V	49.9	17 00	+30 56	52.9	36.2	60
6410		3.13	A3IV	24.1	17 15	+24 50	46.8	31.4	305
6556	α Oph	2.10	A5III	14.3	17 35	+12 34	35.9	22.6	240
6603		2.77	K2III	25.1	17 43	+04 34	29.2	17.2	8
6623		3.42	G5IV	8.4	17 46	+27 43	52.4	25.6	8
6629		3.75	A0V	29.1	17 48	+02 42	28.0	15.4	212
6688		3.74	K2III	34.2	17 54	+56 52	85.2	30.2	8
6703		3.71	G8III	41.5	17 58	+29 15	54.9	23.8	10
6705		2.23	K5III	45.2	17 57	+51 29	79.1	29.2	8
6872		4.32	K2III	70.4	18 20	+36 04	63.5	21.5	8
7001	Vega, α Lyr	0.03	A0V	7.8	18 37	+38 47	67.4	19.2	5
7235		3.00	A0V	25.5	19 05	+13 52	46.9	3.2	360
7405	α Vul	4.45	M0III	90.9	19 29	+24 40	59.0	3.4	
7528		2.90	B9.5IV	52.4	19 45	+45 08	78.7	10.2	128
7557	Altair, α Aql	0.77	A7V	5.1	19 51	+08 52	47.7	−8.9	245
7582		3.83	G8III	44.6	19 48	+70 16	102.4	20.8	10
7635		3.53	M0III	84.0	19 59	+19 30	58.0	−5.2	8

2 OBSERVATIONS

2.1 The Sample Stars

Stars selected for observation were in the RA range 10 to 20 hours, north of the equator, had V magnitude brighter than 4.0, and were at a distance of less than 100 pc. 71 stars met these criteria and 46 of them have been observed. In addition three stars were observed from a supplementary list with a V magnitude limit of 5.0. The stars observed are listed in table 1. This table gives the V magnitude and spectral type as listed in the SIMBAD database, the distance derived from the Hipparcos catalogue parallax (Perryman et al. 1997), the approximate equatorial and galactic coordinates (also from the Hipparcos catalogue) and the $v \sin i$ value, normally from Bernacca & Perinotto (1970), but in a few cases from other sources listed in the SIMBAD database. Previous polarization measurements for the stars are listed in table 2 have been taken from the agglomerated polarization cat-

Table 2. Previous Polarization Measurements

BS	Polarization (Heiles) P(%)	Polarization (Tinbergen)[a] Q/I	U/I	Polarization (Piirola)[a] Q/I	U/I
3982	0.060±0.120	0±7	-4±7	7±11	3± 11
4031	0.050±0.120				
4295	0.000±0.120	4±7	6±7	13±6	3±6
4301	0.040±0.120	3±7	22±7	−3±13	−2±13
4335	0.030±0.120	22±7	−14±7		
4357	0.000±0.120			4±7	−6±7
4359	0.010±0.120	−1±7	−11±7		
4518	0.060±0.120	−33±7	1±7		
4534	0.030±0.120	12±7	3±7	0±14	−12±14
4540	0.042±0.026	4±7	3±7		
4905	0.010±0.120				
4910	0.020±0.120				
4915	0.020±0.120				
4932	0.010±0.120	6±7	−6±7		
5191	0.060±0.000				
5235	0.007±0.012	−6±7	−12±7	−6±9	3±9
5340	0.030±0.120	−1±7	−6±7	−10±8	−11±8
5429	0.030±0.120				
5435	0.000±0.120				
5563	0.100±0.120	6±7	−1±7		
5793	0.060±0.120			14±6	−1±6
5849	0.030±0.120				
5854	0.030±0.120	1±7	0±7		
6092	0.010±0.000				
6095	0.057±0.012				
6149	0.010±0.120				
6212	0.000±0.200				
6410	0.020±0.120				
6556	0.010±0.100	−4±7	−6±6		
6603	0.150±0.120				
6629	0.008±0.001	12±7	15±7		
6688		−36±7	−41±7		
7001	0.020±0.120	11±7	7±7	4±4	6±4
7528	0.030±0.120				
7557	0.016±0.002	15±7	0±7	2±6	−7±6

a - Polarizations in units of 10^{-5}

alogue of Heiles (2000). The measurements of these stars from Heiles (2000) mostly originate from the work of Behr (1959) (all those with errors of 0.12%) with a few measurements from other sources (Schmidt 1968; Klare & Neckel 1977; Markkanen 1979). Only the degree of polarization is listed. The position angle can be found in the original catalogue, but for almost all the measurements the polarization is not significant and the position angle is therefore meaningless.

The Heiles (2000) catalogue does not include some of the most accurate previous polarization measurements of nearby stars made by Piirola (1977) and Tinbergen (1982). These studies include a number of the stars in our sample and are therefore listed separately in table 2. The measurements are in units of 10^{-5} so need to be multiplied by 10 to be compared with the observations reported here. The measurements of Tinbergen were made in three colour bands. We have used, where available, the averaged band I and II measurements, and in other cases the band I measurements. Almost all the previous polarization measurements do not show any significant polarization

2.2 Observation Methods

The observations were obtained with the PlanetPol polarimeter (Hough et al. 2006) mounted on the 4.2m aperture William Herschel Telescope (WHT) which is located at the Observatorio de Roque de Los Muchachos (ORM) at La Palma in the Canary Islands. PlanetPol achieves its high sensitivity through the use of rapid modulation (40kHz) using Photo-Elastic Modulators (PEMs). A three-wedge Wollaston prism is used as the analyser and beam splitter and the light is detected by two avalanche photodiode (APD) detectors. A second identical channel with its own PEM and APDs monitors the sky background.

The polarization measurements are made in a very broad red band covering wavelengths from 590nm to 1000nm. The broad band is necessary to maximise the photon flux in order to achieve the high polarization sensitivity ($\sim 10^{12}$ photons are needed to reduce photon shot noise sufficiently to measure polarization levels of $\sim 10^{-6}$). With such a broad band the precise effective wavelength depends on the colour of the star, and ranges from 735 nm for a B0

V star to 804.4 nm for an M5 V star. Full details are given in table 1 of Hough et al. (2006).

A number of corrections are needed to achieve the 10^{-6} sensitivity (as described in more detail by Hough et al. (2006)). All observations use a "second-stage chopping" procedure in which a periodic rotation of the detectors and Wollaston prism through 90 degrees relative to the PEM is carried out to reverse the sign of the modulation. This was normally done after every 180 seconds of integration. The telescope introduces a small polarization ($\sim 10 - 20 \times 10^{-6}$ for the WHT). This telescope polarization is determined by carrying out observations of stars repeated at several different hour angles. For an altazimuth-mounted telescope like the WHT, the telescope tube rotates about its optical axis relative to the sky (and the polarimeter which is mounted on a rotator that tracks the sky), as the telescope tracks, and this allows the telescope polarization to be separated from the star polarization. A small instrumental polarization $\sim 2 \times 10^{-6}$, (believed to be due to misalignments in the instrument) is determined by repeating measurements with the entire instrument rotated through 90 degrees. Separate measurements with the instrument rotated through 45 degrees are used to determine the Q and U Stokes parameters. These can then be combined to give the degree of polarization and the position angle. Measurements of a number of stars with known large polarizations (~1 – 5 %) are used to determine the instrument's modulation efficiency, which is found to be 98.6% after the known effects of the PEM are allowed for. The same observations are used to determine the position angle zero point which is measured with an accuracy of 1 degree, based on the consistency of the calibration provided by different reference stars, which themselves have uncertainties of this order.

The bulk of the measurements described here were obtained over the period 25 April 2005 to 9 May 2005. Most stars were observed once, using a total integration time of usually 12 minutes for each Stokes parameter. Four stars (BS 4932, BS 5854, BS 5445, BS4534) were observed repeatedly as calibrators for the telescope polarization and the polarizations have been averaged over 4 to 6 observations. The individual measurements for these stars are given by Bailey et al. (2008). Two stars (BS 4295 and BS 4540) were similarly observed as calibrators during February 2006 and the individual observations can be found in Lucas et al. (2009). BS 5793 was observed three times and the three observations have been averaged. BS 3982 was also observed three times and the average of the two best observations has been used. BS 4031 and BS 7001 were both observed twice, but one observation was in significantly better conditions, so only the better of the two observations was used.

2.3 Saharan Dust Correction

As explained by Bailey et al. (2008) and Ulanowski et al. (2007) the nights of May 3 to 7 2005 were affected by an airborne Saharan dust event which introduced a small spurious polarization in the horizontal direction. The excess polariation was negligible at the zenith but increased with zenith distance. Observations on these nights have been handled as follows:

(i) Observations on May 3, the most dust affected night, were not used.

(ii) On May 4 to 7 observations were only used if no other observations for the star were available, and if they were made near the zenith where the effects of the Saharan dust are minimal. All observations were at zenith distance less than 15 degrees on May 4 and less than 20 degrees on May 5-7.

(iii) A correction was applied to these measurements for the dust induced polarization.

(iv) The estimated errors for these observations were increased by adding half the dust correction in quadrature to allow for uncertainties in the precise zenith distance dependence of the dust induced polarization.

The correction for the dust induced polarization has the form:

$$P_{dust} = 1.19 \times 10^{-4}(1 - \cos ZD) \quad (1)$$

for May 4, with the size of the correction on the subsequent nights reduced in proportion to the dust optical depth on these nights. This was found to provide a reasonable fit to the dust affected observations reported by Bailey et al. (2008). The size of the correction was at most 4×10^{-6}, and only four observations required a correction of more than 2×10^{-6}.

2.4 Results

The resulting polarization measurements for the 49 stars are listed in table 3. This table lists the normalized Stokes parameters Q/I and U/I, which are obtained in separate Planetpol observations, and the degree of polarization and position angle obtained by combining the Q/I and U/I measurements. The polarizations and Stokes parameters are in units of 10^{-6} in fractional polarization.

The errors quoted are derived from the internal statistics of the individual data points included in each measurement as described by Hough et al. (2006) and include the uncertainties in the determination of the telescope polarization. As discussed in Hough et al. (2006) and Lucas et al. (2009), analysis of stars with repeated observations suggest that this procedure may somewhat underestimate the true errors (by factors up to 1.8) for the brighter stars in the sample where internal errors of $\sim 1 \times 10^{-6}$ or better are achieved. The quoted errors are probably a better measurement of the true uncertainty for the fainter stars in the sample.

3 DISCUSSION

3.1 Polarization Statistics and Previous Observations

While previous polarization studies of nearby stars have shown very few stars with significant polarization, the much increased sensitivity of our study reveals polarization to be much more common, with 38 stars (77.6% of the sample) having polarizations that exceed 3-sigma. Figure 1 shows a histogram of the measured polarizations and this shows that 24 stars (48.9% of the sample) have polarization above 10^{-5}. Most of the polarizations are, however, relatively small. Only

Table 3. Planetpol Linear Polarization Measurements - The horizontal line marks the 17 hour division used in figure 4

Star	Date(s)[a]	Q/I[b]	U/I[b]	P[b,c]	θ[b]
BS 3982	Apr 26,Feb 20	−34.0±0.8	13.8±0.8	36.7±0.8	78.9±0.8
BS 4031	Apr 29	−11.6±2.4	−8.0±2.4	14.1±2.5	107.3±4.9
BS 4069	Apr 27	−7.5±1.1	−17.4±1.1	18.9±1.1	123.4±1.6
BS 4295	Feb 16-21	5.0±0.9	−8.2±1.0	9.6±1.0	150.7±4.2
BS 4301	Apr 25	2.1±0.9	−9.1±0.9	9.3±0.9	141.6±2.7
BS 4335	Apr 30	−3.0±2.1	−2.4±2.1	3.8±2.1	109.5±15.3
BS 4357	Apr 30	2.7±2.2	−2.5±2.5	3.7±2.4	158.5±18.3
BS 4359	May 5	4.4±2.7	5.3±2.7	6.9±2.7	25.2±11.3
BS 4518	May 6	4.7±2.6	−8.9±2.6	10.1±2.6	148.9±7.3
BS 4527	May 7	−10.9±3.7	−4.2±3.6	11.8±3.7	100.6±8.8
BS 4534	Apr 27-30	0.8±1.1	2.2±1.1	2.3±1.1	35.3±13.9
BS 4540	Feb 18-21	3.3±1.4	−0.1±1.4	3.3±1.4	178.9±10.0
BS 4905	Apr 26	16.5±1.2	0.5±1.3	16.5±1.2	0.8±2.3
BS 4910	Apr 28	1.5±1.6	−2.5±1.5	2.9±1.5	150.8±15.4
BS 4915	May 4	−7.8±2.6	−4.2±2.3	8.8±2.6	104.1±7.6
BS 4932	Apr 27-29, May 8	5.6±1.0	0.6±1.0	5.6±1.0	3.0±3.9
BS 5054	May 8	7.4±1.6	−1.8±1.5	7.6±1.6	173.3±5.8
BS 5191	Apr 25	9.3±1.7	−2.4±2.1	9.7±1.7	172.7±6.1
BS 5235	Apr 27	3.2±1.8	−1.5±1.5	3.5±1.8	167.3±12.9
BS 5340	May 9	3.0±1.4	5.5±1.6	6.3±1.6	30.6±6.7
BS 5429	May 4	−3.7±2.2	−9.6±2.5	10.3±2.4	124.5±6.2
BS 5435	Apr 27-30	−2.8±1.6	−2.2±1.6	3.6±1.6	108.6±9.8
BS 5563	May 9	8.2±2.2	1.9±1.8	8.4±2.2	6.5±6.3
BS 5793	Apr 25-26	−3.9±1.2	0.0±1.0	3.9±1.2	90.0±7.2
BS 5849	May 7	−0.4±3.3	0.0±3.7	0.4±3.3	90.7±235
BS 5854	Apr 27-30, May 8	−2.3±0.9	3.9±1.0	4.5±0.9	59.7±6.1
BS 6092	Apr 28	−234.6±3.3	−19.7±3.4	235.4±3.3	92.3±0.4
BS 6095	May 5	−1.3±2.5	13.2±2.9	13.3±2.9	47.9±5.3
BS 6148	Apr 26	12.3±1.4	14.1±1.3	18.7±1.3	24.5±2.1
BS 6149	Apr 29	10.6±3.3	3.6±3.0	11.2±3.3	9.4±7.6
BS 6212	May 4	−2.2±2.6	9.3±2.6	9.6±2.6	51.6±7.8
BS 6299	Apr 29	−7.4±1.7	9.4±1.4	11.9±1.5	64.2±3.9
BS 6324	May 4	−8.3±4.1	9.2±3.7	12.4±3.9	65.9±9.1
BS 6410	May 5	−5.3±2.4	5.8±2.4	7.9±2.4	66.1±8.8
BS 6556	Apr 27	11.1±2.0	20.6±2.0	23.4±2.0	30.8±2.4
BS 6603	Apr 27	18.1±2.1	26.6±2.2	32.2±2.1	27.9±1.9
BS 6623	May 6	6.9±2.2	6.2±1.9	9.3±2.1	20.9±6.2
BS 6629	May 8	22.2±3.0	34.3±3.2	40.8±3.1	28.5±2.1
BS 6688	Apr 28	−0.8±3.3	3.7±2.9	3.8±2.9	50.8±25.3
BS 6703	May 4	22.8±2.4	8.4±2.4	24.3±2.4	10.1±2.8
BS 6705	Apr 28	25.1±1.2	−68.8±1.2	73.3±1.2	145.0±0.5
BS 6872	May 7	104.1±2.7	22.5±2.7	106.5±2.7	6.1±0.7
BS 7001	May 6	6.2±1.0	16.1±1.0	17.2±1.0	34.5±1.4
BS 7235	May 4	−13.0±3.0	18.7±3.0	22.8±3.0	62.4±3.8
BS 7405	May 7	175.3±2.3	1309.7±3.1	1321.4±3.1	41.2±0.1
BS 7528	May 8	75.6±2.0	77.0±2.1	108.0±2.0	22.8±0.5
BS 7557	Apr 26	−7.3±1.3	−1.2±1.2	7.4±1.3	94.6±4.7
BS 7582	May 8	−0.9±2.7	1.2±2.5	1.5±2.6	62.8±50.3
BS 7635	Apr 26	−75.1±1.5	184.9±1.4	199.5±1.4	56.1±0.2

a - April and May dates are 2005, February dates are 2006
b - All polarizations are in units of 10^{-6}, position angles are in degrees.
c - P is calculated from $P = \sqrt{(Q/I)^2 + (U/I)^2}$

9 stars in the sample have polarizations above 2.5×10^{-5}, and only two exceed 2×10^{-4}.

Hence it is not surprising that previous surveys of the polarization of nearby stars, with precisions of at best $\sim$7 $\times$ 10^{-5} (Tinbergen (1982) and Piirola (1977)), detected few polarized stars. For these surveys a 3-sigma detection would require a polarization of at least 2.1×10^{-4}, and only BS 7405 in our sample has a large enough polarization to be clearly detected. However, this star, and our two next highest polarizations BS 6092 and BS 7635 were not observed in either of these previous studies.

Tinbergen (1982) did report marginally significant polarizations in three of our sample stars, BS 4335, BS 4518

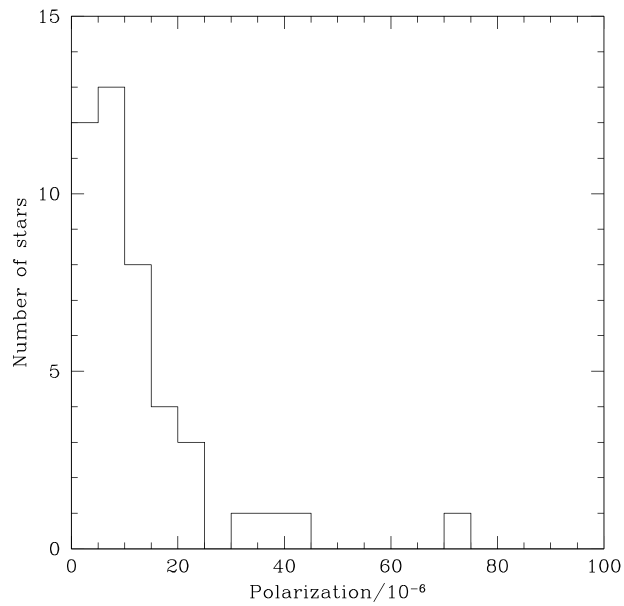

Figure 1. Histogram of polarizations of stars in the sample. There are 5 stars in the sample with P > 10^{-4} and therefore not shown here.

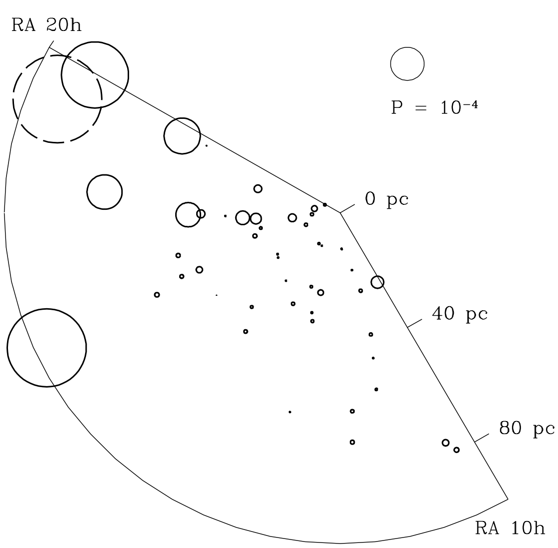

Figure 2. Spatial distribution of polarization in the sample. The size of the circle is proportional to the degree of polarization, except for the dashed circle which represents BS7405 and is shown 5 times smaller than its correct size.

and BS 6688. However, all these stars show very low polarization in our observations.

In table 4 the polarization properties as a function of spectral type are listed. Across the spectral classes A, F, G and K the median polarizations, and the percentage of stars with polarization greater than 15 × 10^{-6} are very similar. Tinbergen (1982) suspected the presence of variable intrinsic polarization at the 10^{-4} level in stars with spectral type F0 and later. This is not supported by our more sensitive observations. Higher polarizations are indicated for spectral classes B and M, but we have very few stars of these types, and they are at larger average distances, so this result is almost certainly a consequence of the polarization distance relation we find in the next section, and not a consequence of any intrinsic polarization of these stars.

Table 4. Polarization for spectral types

Spectral Type	N	Mean Dist	Median Poln	Percent > 15 × 10^{-6}
B	5	49.6	36.8 × 10^{-6}	60
A	18	28.1	8.4 × 10^{-6}	28
F/G	9	23.5	9.4 × 10^{-6}	22
K	12	38.7	9.8 × 10^{-6}	25
M	4	78.6	109.2 × 10^{-6}	75

3.2 Polarization Spatial Distribution

The spatial distribution of the observed polarizations is shown in figures 2 and 3. The distribution is quite striking. Figure 2 shows that there is very little polarization in the RA range 10 to 16 hours, and that most of the high polarizations are found in the range 16 to 20 hours. Within this RA range there is a strong correlation with distance, with the highest polarizations being found at the greatest distances.

In figure 3 it can be seen that the high polarizations correspond to lower galactic latitudes. Stars around the galactic pole have generally low polarizations and substantial polarizations begin to appear for galactic latitudes below about 40 degrees. It is also apparent from the polarization vectors that the position angles are not random, but show a tendency for the polarization direction to be along lines of galactic latitude. This implies a galactic magnetic field in the solar vicinity that lies in the galactic plane. These correlations with position strongly suggest that the bulk of the polarization being observed is interstellar in origin, and not intrinsic to the stars.

Figure 4 shows the variation of polarization with distance. Studies of the interstellar polarization of more distant stars have shown that fractional polarization increases with distance at about 2 × 10^{-5} pc^{-1} (Behr 1959). The studies of Tinbergen (1982) and Leroy (1993b) have shown that the polarization of nearby stars is less than would be expected from this relationship. Figure 4 shows just how low polarizations near the Sun are compared with this relationship. The open circles on this figure, which represent stars at RA less than 17h and corresponds to regions around the north galactic pole, actually fit a relationship of about 2 × 10^{-7} pc^{-1}, about 100 times less than that for distant stars. This indicates that the interstellar medium in this direction has about a factor of 100 less dust than the typical value for the interstellar medium in the galactic plane.

The lower panel of figure 4 shows an expanded view of the polarization data for RA <17h. The polarization data used in figure 4 have been debiased by plotting $\sqrt{P^2 - \sigma_P^2}$ where σ_P is the error in polarization given in table 3. This is a standard method of correcting for the fact that polariza-

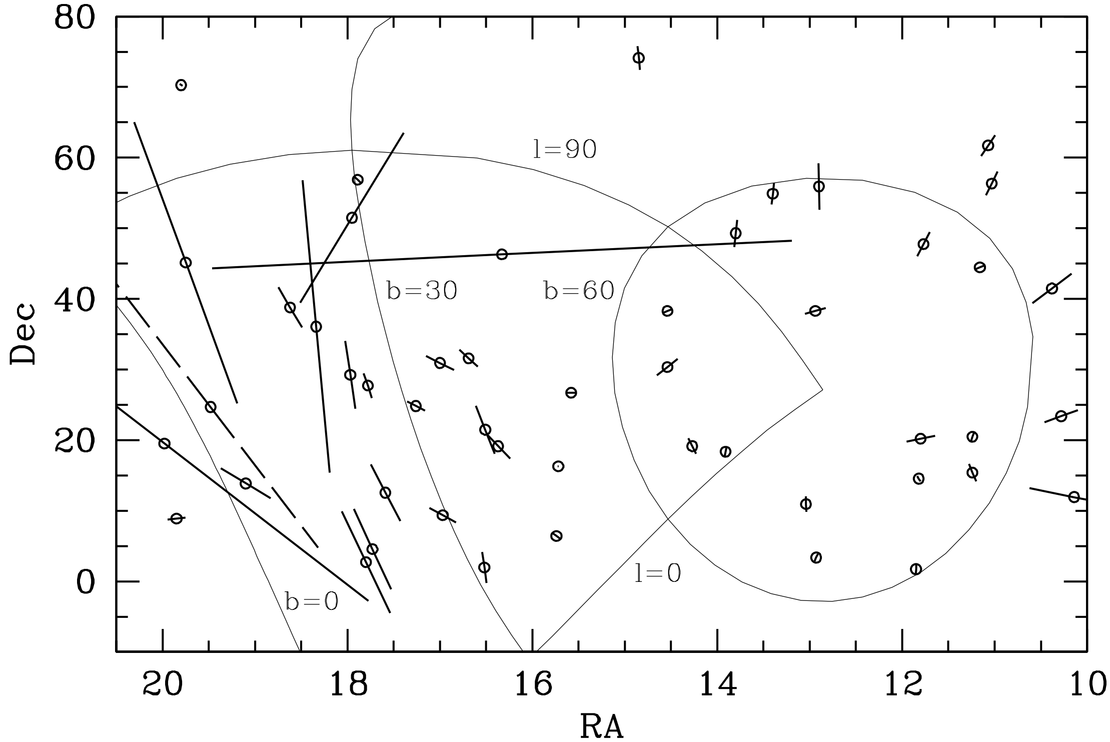

Figure 3. Polariation vectors plotted against position. Lines of galactic latitude 0, 30 and 60, and galactic longitude 0 and 90 are shown. The dashed vector represents BS7405 and is shown 10 times smaller than its correct size.

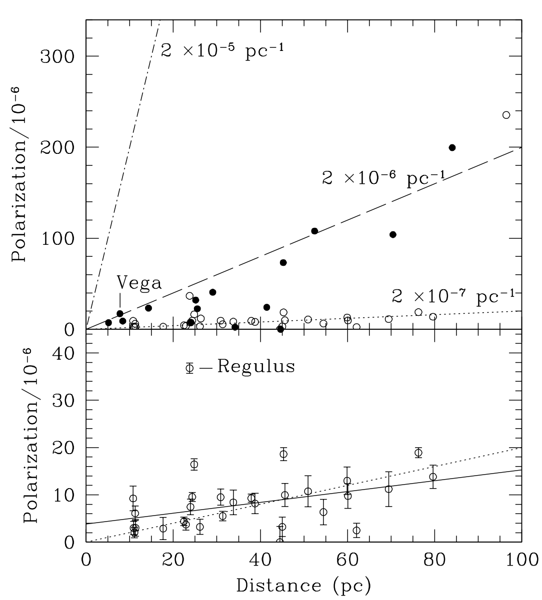

Figure 4. Polarization plotted against distance. Solid symbols are stars with RA $>$ 17h and open symbols are stars with RA $<$ 17h. The dot-dash line shows the polarization versus distance relation for distant stars and the dash and dotted lines are relationships with 10 and a 100 times less polarization per parsec. The lower panel is an expanded view of the data for stars with RA $<$17h. The solid line is the least squares fit to the data excluding Regulus and BS 6092

tion values are always positive and can therefore be significantly biased toward larger values where P is comparable with σ_P. Even at these low polarization levels there is an indication that polarization increases with distance. The solid line in the lower panel of figure 4 is the least squares fit to the data (excluding Regulus and BS 6092). The correlation coefficient is 0.469 and the probability of this occurring by chance is less than 2%. This demonstrates that even in this low polarization region we are seeing a contribution from interstellar polarization. It does not rule out small amounts of polarization from other sources, but neither are other mechanisms required. An imperfect correlation with distance is expected due to the patchy nature of the density of the interstellar medium.

In the region nearer the galactic plane shown by the solid symbols in figure 4 the polarizations are higher and some measurements fit an increase with distance of about 2×10^{-6} pc^{-1} about a factor 10 less than the value for distant stars. However, many points fall well below this line suggesting that the dust in this region is very clumpy.

Polarization is related to the amount of interstellar dust along the line of sight. However, the degree of polarization will also depend on the efficiency of grain alignment, and on the angle of the magnetic field to the line of sight. The relationship between polarization and extinction $E(B-V)$ for more distant stars, shows that the maximum polarization is given by $P(\%) \sim 9E(B-V)$ (Schmidt 1968), corresponding to maximum grain alignment, but actual values show a great deal of scatter and can fall well below this maximum value. Fosalba et al. (2002) give a mean relationship of $P(\%) = 3.5E(B-V)^{0.8}$.

If we apply this relationship to the two lower lines shown on figure 4, then the lines correspond to a $E(B-V) = 0.00157$ at 100 pc for the line that roughly fits the galactic plane polarizations, and $E(B-V) = 0.000037$ at 100 pc for the lower line that fits the galactic pole polarizations. These $E(B-V)$ values are well below those that can actually be measured by photometry.

The relationship between polarization and angle to the line of sight should lead to a polarization that depends on galactic longitude. This is difficult to test with our data, since the stars near the galactic plane are restricted to a small range of galactic longitude. A more extensive survey, might reveal such effects.

3.3 Polarization and the Local Cavity

The distribution of polarization we observe is consistent with other data on the local interstellar medium that shows the presence of a local cavity or local bubble in the solar vicinity (Cox & Reynolds 1987; Lallement 2007). For example, studies of the 3D distribution of interstellar gas using Na I D line absorption (Lallement et al. 2003), show little interstellar gas near the Sun and towards the north galactic pole, but show that significant gas is detected quite close to the Sun (∼50 pc) in the galactic plane between galactic longitudes 0 and 90, the direction in which we see the largest polarizations. This suggests that the distribution of dust shown by the polarization is similar to the gas distribution revealed by the Na I absorption measurements. A similar distribution of interstellar material is shown in the local hot bubble (LHB) revealed in soft X-ray background observations (Snowden et al. 1998) which appears to lie within the cavity seen in Na I absorption.

Our polarization observations confirm the presence of a Local Cavity with little interstellar material within 100pc of the Sun, but nevertheless suggest that there is some interstellar dust within this region that can be detected by high-sensitivity polarimetry. It is less clear whether the polarization observations define a sharp edge to the local cavity. The large polarizations observed for BS 7405 and BS 6092, two of the most distant stars in our sample, may be indicative of such an edge, but there are too few stars at this distance to determine if such polarizations are typical of this distance (∼90 pc).

We are also unable to directly look at correlations between polarization and sodium absorption on an individual sight line basis, as there is only one star common to our sample and the Na I observations of Lallement et al. (2003) and Sfeir et al. (1999), and this star has both small polarization and no significant D line absorption.

While we cannot directly compare with Na I D line absorption, there are a number of measurements of Ca II H&K absorption for nearby early-type stars included in our sample. Ca II absorption is seen in sight lines towards nearby stars that do not show significant neutral gas as seen in Na I absorption. The Ca II absorption is thought to result from warmer gas present in the local cavity. In many cases there are several distinct velocity components seen in the CaII absorption indicating the presence of discrete clouds. In figure 5 we show Ca II column density for nine stars from our sample. The CaII data are taken from Redfield & Linsky (2002) and are originally

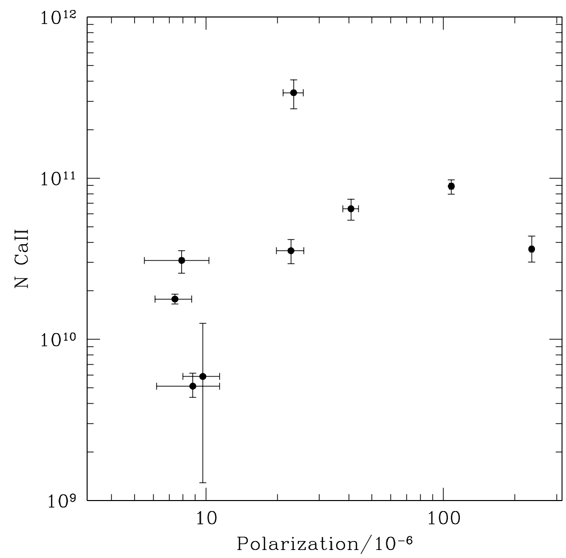

Figure 5. Ca II column density plotted against polarization for nine stars

from Bertin et al. (1993), Crawford, Lallement & Welsh (1998), Lallement & Bertin (1992), Vallerga et al. (1993) and Welty, Morton & Hobbs (1996). Where multiple velocity components are observed, the column density has been summed over all components. Figure 5 shows a slight tendency for higher Ca II column densities at higher polarizations, but there is much scatter and no strong correlation. This suggests that the dust responsible for the polarization is not located in the clouds responsible for the Ca II absorption.

3.4 Individual Stars

BS 3982 (Regulus) stands out as having a high polarization compared with stars in its RA range despite being at a relatively small distance of 23.8pc. Two observations of its polarization in 2005 April and 2006 February are in excellent agreement. Regulus is known to be a rapidly rotating B star, and its rotational flattening has been measured directly by interferometry. McAlister et al. (2005) used the CHARA array to determine the rotational flattening of Regulus and derive a position angle of the minor axis of 85.5 ± 2.8 degrees. This is in agreement with our measured polarization position angle of 78.9 ±0.8 degrees.

A rotationally flattened early type star is expected to show polarization as a result of electron scattering in its non-spherically symmetric atmosphere. Sonneborn (1982) calculates the polarization expected in rapidly rotating B stars. The polarization is parallel to the rotation axis at red wavelengths as observed for Regulus. The degree of polarization decreases with spectral subclass from about 0.01% (100×10^{-6}) at B2 to about 0.005% (50×10^{-6}) at B5, the latest spectral class modelled. Our measured polarization for Regulus (B7) of 36.7×10^{-6} is therefore in good agreement with these calculations. However, Sonneborn (1982) calculates the polarization for a star rotating with 95% of its critical velocity for break-up, whereas according to McAlister et al. (2005) Regulus is only rotating at 86% of its critical velocity. It is therefore important to carry out polarization calculations for rapidly rotating stars that include a wider range of parameters. However, the fact that we see unusual polarization for Regulus, and this star stands out in our sample as having both rapid rotation and an early spectral type (needed to give an electron scattering atmosphere), strongly suggests that the polarization arises from rotational flattening. If this interpretation is correct it would be the first observation of this effect.

BS 7001 (Vega) shows a polarization of $17.2 \pm 1.0 \times 10^{-6}$ at a position angle of 34.5 ± 1.4 degrees. Vega is known to possess a debris disk detected by its infrared excess (Aumann et al. 1984). Scattering of light from dust in the disk is therefore a potential source of polarization, as has been observed in the case of the Beta Pictoris disk (Gledhill, Scarrott & Wolstencroft 1991; Tamura et al. 2006). However, the Vega disk is large. Spitzer observations show it extending out to 105 arc seconds at 160 μm (Su et al. 2005) and it is circular indicating that the disk is seen face-on. The Spitzer observations also indicate an inner radius for the disk of 11 ± 2 arc seconds. Since the PlanetPol observations used an aperture of 5 arc seconds this would mean that the observations did not include the disk. However, there is also evidence for circumstellar material within 1 arc second of Vega (Absil et al. 2006). The face-on nature of the system is supported by interferometric observations of Vega that show it to be a rapidly rotating star seen almost pole-on (Peterson et al. 2006; Aufdenberg et al. 2006), with an inclination measured to be 4.7 ± 0.3 (Aufdenberg et al. 2006) or 4.55 ± 0.33 degrees (Peterson et al. 2006).

There have been no detections of the Vega disk in scattered light. Mauron & Dole (1998) attempted to detect scattered light through polarization at distances of 7 to 30 arc seconds for the star, and detected no polarization with limits about 200 times lower than the disk of Beta Pic. A face-on disk with material symmetrically distributed around the star would not be expected to show any polarization in observations centered on the star. Thus our observed polarization could only result from the circumstellar disk if there is an asymmetric distribution of circumstellar material close to the star.

An alternative explanation of the Vega polarization is that it is interstellar in origin. This may seem unlikely for a star at a distance of only 7.8 pc. However, Vega is located in the region of the sky where we see the largest interstellar polarizations. The polarization would correspond to 2.2×10^{-6} pc^{-1}, which is similar to that seen in more distant stars in this RA range, as seen in figure 4. The position angle of 35 degrees is similar to that of other stars in the region.

3.5 Interstellar Dust in the Heliosphere

Frisch (2005) has argued that the weak polarization of nearby stars observed by Tinbergen (1982) could be due to interstellar dust entrained in the magnetic wall of the heliosphere. This was based on the presence of a spatial distribution of polarization that was related to ecliptic coordinates, and the absence of a significant distance dependence of the polarization. Our results do not support this interpretation for polarization of nearby stars. Figures 2 and 4 show clearly that polarization is correlated with distance and that the dust responsible must therefore be widely distributed over the 100 pc scale covered by our observations.

4 CONCLUSIONS

Polarization measurements of a sample of 49 nearby bright stars have been measured to accuracies about 20 to 100 times better than those of any previous measurements. In contrast to previous observations which have generally been unable to detect many polarized stars at these distances, we find significant polarization in many of the stars. The polarization increases with distance and shows much higher values at low galactic latitudes than towards the galactic pole. The distribution of polarization strongly suggests that the high polarization stars and probably most of the lower polarization stars, are showing interstellar polarization. The results indicate that polarization measured at the parts per million level provides a very sensitive probe of the interstellar medium in the solar vicinity.

The polarization observed near the Sun is much less than would be expected based on the polarization of distant stars, thus confirming the presence of the local cavity or bubble seen in absorption line measurements and in the soft X-ray background. Polarization shows litle correlation with CaII absorption due to warm interstellar gas. The data is not consistent with the hypothesis of Frisch (2005) that polarization in nearby stars is due to interstellar dust entrained in the heliospere.

Regulus shows a larger polarization than expected for its position. Regulus is known to be a rapidly rotating star, and the polarization direction agrees with the minor axis of the rotational flattening as measured by interferometry. The polarization is reasonably consistent with that expected due to electron scattering in the atmosphere of the flattened star.

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